

RECONSTRUCTING THE GUITAR: BLOWING BUBBLES WITH A PULSAR BOW SHOCK BACK FLOW

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Accepted July 11, 2008, for publication in ApJ (Letters)

ABSTRACT

The Guitar Nebula is an H α nebula produced by the interaction of the relativistic wind of a very fast pulsar, PSR B2224+65, with the interstellar medium. It consists of a ram-pressure confined bow shock near its head and a series of semi-circular bubbles further behind, the two largest of which form the body of the Guitar. We present a scenario in which this peculiar morphology is due to instabilities in the back flow from the pulsar bow shock. From simulations, these back flows appear similar to jets and their kinetic energy is a large fraction of the total energy in the pulsar's relativistic wind. We suggest that, like jets, these flows become unstable some distance down-stream, leading to rapid dissipation of the kinetic energy into heat, and the formation of an expanding bubble. We show that in this scenario the sizes, velocities, and surface brightnesses of the bubbles depend mostly on observables, and that they match roughly what is seen for the Guitar. Similar instabilities may account for features seen in other bow shocks.

Subject headings: pulsars: individual (PSR B2224+65) — ISM: individual (Guitar Nebula) — ISM: bubbles — ISM: jets and outflows — instabilities

1. INTRODUCTION

Many pulsars travel at high speed, and the collision between their relativistic winds and the interstellar medium leads to the formation of bow shocks. These shocks are observed most readily at X-ray and optical wavelengths: the shocked relativistic wind will emit mostly synchrotron radiation, while the shocked interstellar medium will emit – if it is partially neutral – copious H α emission (for a review, see Gaensler & Slane 2006).

Arguably the most spectacular bow shock is the Guitar Nebula, made by one of the fastest pulsars known, PSR B2224+65 (Cordes, Romani, & Lundgren 1993). This H α nebula has, as the name implies, a guitar-like shape, with a bright head, a faint neck, and a body consisting of two larger bubbles (see Fig. 1). Cordes et al. (1993) suggest this morphology might reflect variations in either the pulsar energy injection rate or the interstellar medium density.

In this *Letter*, we investigate whether instead the peculiar morphology could be due to instabilities in the jet-like flow of pulsar effluvium away from the bow shock. Fast back flows are a natural consequence of bow shocks: the pulsar wind is greatly heated at the shock, which, for the usual case where cooling is slow, leads to a high pressure that drives a flow in the only direction available, to the back. From simulations (e.g., Bucciantini et al. 2005), the flows seem similar to jets, being well-collimated and fast, and seem to carry most of the pulsar wind energy. Jet-like flows are indeed seen in X-ray observations, which also show that only a small fraction of the energy is radiated (for a review, Kargaltsev & Pavlov 2008).

So far, the simulations have not extended far to the back, but if the back flow is similar to a jet, one might expect it to become unstable further downstream. From simulations of jets (e.g., Bodo et al. 1998), this instability would lead to mixing with the ambient medium and rapid dissipation of the kinetic energy into heat. The simulations have not followed what happens beyond this initial mixing, but it seems plausible that the material would expand rapidly and drive a bubble. If so, it might initially expand faster than the pulsar motion, and gain further energy from the jet. With time, however, it will slow down, and once the pulsar has moved sufficiently

far ahead, the jet will become so long that it becomes unstable before reaching the bubble, and a new bubble will be formed. We suggest the body of the guitar is made up of two such bubbles, while another one has just started to form near the head.

In § 2, we describe our model in more detail, and in § 3 we compare it with the properties of the Guitar Nebula, finding qualitative agreement. In § 4, we discuss implications as well as ways in which our model could be tested.

2. BLOWING BUBBLES WITH A BOW SHOCK BACK FLOW

We consider a pulsar that loses energy at a rate \dot{E} in the form of a relativistic wind and moves at velocity v_* through a medium of density ρ_0 . The resulting bow shock will have a stand-off distance r_0 given by

$$\frac{\dot{E}}{4\pi r_0^2 c} = \rho_0 v_*^2. \quad (1)$$

The bow shock leads to a jet-like back flow carrying kinetic energy at a rate $f_E \dot{E}$, where from simulations the efficiency factor f_E is close to unity (Bucciantini 2002). We assume the back flow will become unstable some distance ℓ behind the neutron star, rapidly mix with shocked ambient medium and dissipate its energy, leading to the formation of a bubble. Assuming also that the bubble is fed more energy for some time t_{inj} , and expands adiabatically for a total time t_{exp} , the bubble radius will be approximately given by the Sedov-Taylor solution,

$$R_b = \eta_\gamma \left(\frac{f_E \dot{E} t_{\text{inj}}}{f_\rho \rho_0} \right)^{1/5} t_{\text{exp}}^{2/5}, \quad (2)$$

where η_γ is a dimensionless constant of order unity that depends on the adiabatic index of the interstellar medium and the extent to which energy injection is instantaneous (see below), and f_ρ takes account of possible variations in density between the head of the bow shock and the location of the bubble (for our model, by assumption, $f_\rho \simeq 1$).

Eq. 1 and 2 both depend on the ratio \dot{E}/ρ_0 , suggesting the bubble radii can be expressed in terms of bow-shock properties and other observables. For this purpose, we rewrite Eq. 1

as,

$$\frac{\dot{E}}{\rho_0} = \frac{4\pi c}{v_* f_i^2 \sin^3 i} d^5 \mu_*^3 \theta_0^2, \quad (3)$$

where i is the inclination, d the distance, $\mu_* = v_* \sin i / d$ the proper motion, and $\theta_0 = f_i r_0 / d$ the angular stand-off distance (f_i is a function of the inclination, with $f_{90^\circ} = 1$, but $f_i \neq \sin i$; see Gaensler et al. 2002). We also write $t_{\text{exp}} = (\alpha - \lambda) / \mu_*$, where α is the angular separation between the center of the bubble and the pulsar and $\lambda = \ell \sin i / d$ the angular size corresponding to the instability length ℓ , and $t_{\text{inj}} = (\beta - \Delta\lambda) / \mu_*$, where β is the separation between the center of the bubble and the next one closer to the pulsar, and $\Delta\lambda$ takes into account that two bubbles can have formed at slightly different distances behind the pulsar. Note that for the bubble closest to the pulsar, $t_{\text{inj}} = t_{\text{exp}}$ and one should replace $\beta - \Delta\lambda$ with $\alpha - \lambda$ below. With this, the angular radius of a bubble, $\theta_b = R_b / d$, is given by,

$$\theta_b = f_b \left(\frac{4\pi c}{v_*} \right)^{1/5} (\theta_0^2 (\alpha - \lambda)^2 (\beta - \Delta\lambda))^{1/5}, \quad (4)$$

where $f_b = \eta_\gamma (f_E^2 / f_p f_i^2 \sin^3 i)^{1/5}$ is of order unity. One sees that for a bubble far behind the pulsar (i.e., $\lambda \ll \alpha$ and $\Delta\lambda \ll \beta$), there is little room to fiddle: the uncertainties in the efficiency factors, geometry, and velocity may amount to a factor two, but they enter only to low power.

With the sizes, the expected $\text{H}\alpha$ photon rates are given by,

$$n_{\alpha,b} = \frac{f_\alpha 4\pi R_b^2 v_b n_{\text{H}^0}}{4\pi d^2} = f_\alpha n_{\text{H}^0,b} \theta_b^2 \mu_b d, \quad (5)$$

where f_α is the number of $\text{H}\alpha$ photons emitted per neutral particle before that particle is ionised (~ 0.05 and 0.27 for case A and B, resp., weakly dependent on velocity; Chevalier & Raymond 1978), n_{H^0} the neutral hydrogen number density, v_b the expansion rate, and μ_b the corresponding proper motion,

$$\mu_b = \frac{2}{5} \mu_* \frac{\theta_b}{\alpha - \lambda}, \quad (6)$$

where the coefficient becomes $3/5$ for the bubble closest to the pulsar. Observationally, it is easiest to measure surface brightnesses near the limbs of bubbles. For measurement length scales $\delta \ll \theta_b$, one predicts $s_{\alpha,\text{limb}} = n_{\alpha,b} (1/2\pi\delta\theta_b) \sqrt{2\delta/\theta_b} \propto \mu_b \theta_b^{1/2}$.

We now discuss our assumptions and simplifications. Our three main premises are that the back flow is jet-like; that it becomes unstable; and that the instability drives a bubble that is fed further energy for some time. The first two are supported by simulations: bow shocks appear to give jet-like back flows with $r_{\text{jet}} \simeq 4r_0$ (Bucciantini et al. 2005), and jets do seem to become unstable (with much of the recent work focussing on how to prevent this from happening too quickly; for a review, e.g., Hardee 2004). Typically, perturbations appear to grow on length scales ℓ_g about ten times the jet radius r_{jet} . For instance, for relativistic jets in a ten times denser medium, Hardee et al. (1998) found $4 \lesssim \ell_g / r_{\text{jet}} \lesssim 15$. For a bow shock, this implies angular growth length scales λ_g in the range $16 \lesssim (\lambda_g / \theta_0) (f_i / \sin i) \lesssim 60$. Of course, instability will only occur after a few growth times, so the angular distance λ should be correspondingly larger. We will see in § 3 that this is consistent with the Guitar Nebula. It also validates an implicit assumption we made, that the bubbles do not overtake the pulsar, i.e., that $\alpha > \theta_b$ at all times. From Eq. 4, the minimum

value of $\alpha - \theta_b$ occurs at $\alpha = \lambda + \theta_0 (3f_b/5)^{5/2} (4\pi c / v_*)^{1/2}$; this becomes negative only for $v_* \lesssim 50 f_b^{5/2} (50\theta_0 / \lambda)^2 \text{ km s}^{-1}$, much smaller than the velocity of PSR B2224+65.

What is not clear yet, however, is whether jet instabilities could lead to bubbles, and, if so, whether our simplified description is justified. In particular, in using the Sedov-Taylor solution, we assume energy is injected (nearly) instantaneously at a single point in a homogeneous medium, and that the expansion is adiabatic. Of these assumptions, the last is reasonable: the cooling time, $t_{\text{cool}} \approx 20000 \text{ yr} (v_b / 100 \text{ km s}^{-1})^3 (\rho_0 / 10^{-25} \text{ g cm}^{-3})^{-1}$ (Koo & McKee 1992), is much longer than the $\sim 300 \text{ yr}$ it takes PSR B2224+65 to cross the nebula (here, we scaled to the lowest velocities and highest densities appropriate for the Guitar Nebula). The others are less realistic: energy will be injected some time in a larger, not necessarily spherical volume embedded in a medium which, close to the axis, has been through the bow shock. Injection over some time should lead to a bubble that initially expands somewhat more slowly. Indeed, Dokuchaev (2002) found that for continuous energy injection, Eq. 2 can be used, but with a somewhat smaller value of η_γ (e.g., $\eta_{5/3} = 0.929$ for $t_{\text{exp}} = t_{\text{inj}}$ instead of $\eta_{5/3} = 1.152$ for $t_{\text{inj}} \ll t_{\text{exp}}$). This may be counteracted, however, by the initial expansion being in pre-shocked, less dense medium. At later times, our estimates should depend less on these initial conditions, but rather on the extent to which bubbles can be treated in isolation, when in the Guitar Nebula they appear to have merged (Fig. 1). Overall, we conclude that our heuristic model will only be good at the factor 2 level.

3. RECONSTRUCTING THE GUITAR

To see how well our model applies to the Guitar Nebula, we retrieved a deep $\text{H}\alpha$ image taken on 6 Dec. 2000 for the Champlane survey (Zhao et al. 2005), and measured properties of what seemed the three most obvious bubbles (see Fig. 1 and Table 1): the two forming the body of the guitar, and one just behind the pulsar (hereafter, bottom, middle, and head). For all bubbles, the estimates of the angular separation from the pulsar, α , and of the angular radius, θ_b are quite reliable, but for the middle bubble, the separation to the next closest bubble, β , is relatively poorly defined, since there may be an additional bubble in the neck.

For our estimates, we also need the stand-off distance θ_0 . Chatterjee & Cordes (2004) find that the shape of the bow shock – as seen in $\text{H}\alpha$ images taken with the *Hubble Space Telescope* (*HST*) – is reproduced well with the analytic model of Wilkin (1996). For data sets taken in 1994 and 2001, they infer inclinations $i \simeq 90^\circ$ and stand-off radii $\theta_\alpha = 0''.12 \pm 0''.04$ and $0''.15 \pm 0''.04$, respectively. Since $\text{H}\alpha$ is emitted outside the actual stand-off distances, with $\theta_\alpha \simeq 1.5\theta_0$ (Bucciantini 2002), one infers $\theta_0 \simeq 0''.09$, which we will use below. We will also use the observed proper motion of $\mu_* = 0''.182 \text{ yr}^{-1}$ (Harrison et al. 1993) and scale the pulsar speed to $v_* = 1500 \text{ km s}^{-1}$ (where we used $i \simeq 90^\circ$ and a distance $d = 1.8 \text{ kpc}$, as implied by the dispersion measure of 35.30 pc cm^{-3} and the NE2001 electron density model of Cordes & Lazio 2002).

3.1. Sizes

In matching our model to the measurements, we first note that the existence of the head bubble implies $\lambda < 9''$. Thus, for the bottom bubble, $\lambda \ll \alpha$ and $\Delta\lambda \lesssim \lambda \ll \beta$. For this case, Eq. 4 simplifies to $\theta_b = f_b (4\pi c / v_*) \theta_0^2 \alpha^2 \beta^{1/5} = 18''/3f_b$;

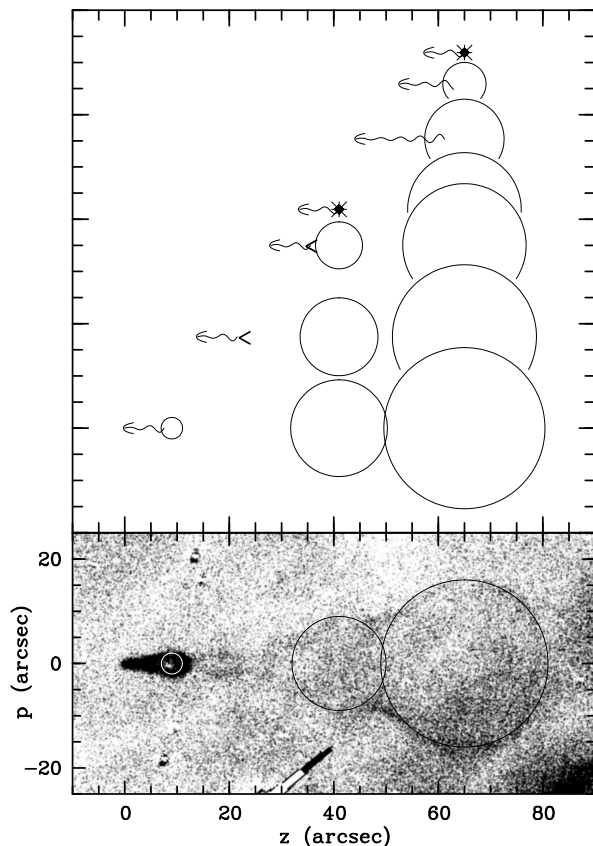


FIG. 1.— Reconstructing the Guitar. (*Top*) A possible sequence of events that could have led to the guitar nebula, using instabilities in the jet-like pulsar back flow. The instabilities are set to occur at the positions marked with a star, roughly $8''$ behind the pulsar. They lead to a rapid dissipation of energy and spherical expansion, and are fed for a while, until an instability occurs closer to the pulsar. To match roughly the image of the guitar, we have to assume that the instabilities occurred rather closely together in the region marked with $<$ signs, so that no distinct bubbles formed. (*Bottom*) Continuum-subtracted $H\alpha$ image from the Champlane survey, with suggested locations of bubbles overlaid.

to match the observed radius of $16''$ thus requires $f_b \simeq 0.9$, close to unity as expected.

Using this value of f_b for the head bubble, we find we require $\lambda \simeq 7.5$ to match the observed small size of $2''$. This implies $\lambda/\theta_0 \simeq 80$, in line with expectations (§ 2). It also implies the bubble formed only recently, about $(\alpha - \lambda)/\mu_* \simeq 8$ yr before the image was taken. We return to this below.

For the middle bubble, we find that to match its observed size requires $\beta - \Delta\lambda \simeq 5.5$. This is much smaller than for the bottom bubble, since to produce this relatively small bubble requires much less energy. It raises the question, though, what happened to the energy dissipated later, outside the middle bubble. One possibility is that more energy was injected in the middle bubble, but that it grew, it merged and equilibrated with the larger bottom bubble. If so, our above estimate of f_b would be too large. Clearly, we have reached the limits of applicability of our simplistic picture of individual, spherical bubbles.

3.2. Proper motions and brightnesses

Our model predicts expansion rates (see Table 1). For the head bubble, the predicted rate is fast, $\sim 0.15 \text{ yr}^{-1}$. By comparing *HST* images, Chatterjee & Cordes (2004) indeed find that the head bubble expanded between 1994 and 2001, especially to the back, at a rate comparable if slightly slower than that predicted, of $\sim 0.10 \text{ yr}^{-1}$. Interestingly, the bubble

TABLE 1
BUBBLES IN THE GUITAR NEBULA

ID	α ($''$)	θ ($''$)	β ($''$)	μ ($'' \text{ yr}^{-1}$)	$s_{\alpha, \text{limb}}$	λ ($''$)
Head, observed	9	2		0.10	0.47	
model		2.1		0.15		7.5
Middle, observed . .	41	9	< 32	...	0.09	
model		9.3	5.5	0.02	0.13	7.5
Bottom, observed . .	65	16	24	...	0.13	
model		15.4		0.02	0.17	7.5

NOTE. — For each bubble, the first row lists measured parameters: α , the angular separation between the centre of the bubbles and the pulsar; θ , the angular radius; β , the separation to the next bubble (undefined for the head bubble); μ , the expansion rate; and $s_{\alpha, \text{limb}}$, the surface brightness near the limb (relative to that at the position of the pulsar, which, from the instrumental sensitivities, has a photon rate of $1.0 \times 10^{-4} \text{ s}^{-1} \text{ cm}^{-1} \text{ arcsec}^{-2}$, with an uncertainty of about 20%). The second row lists model assumptions and predictions, including λ , the angular wavelength of instability. Empty entries indicate that observed values were used. Limb surface brightnesses for the middle and bottom bubble were calculated relative to the observed brightness for the head bubble, using that $s_{\alpha, \text{limb}} \propto \mu \theta^{1/2}$ (see § 2).

also became brighter, consistent with the idea that it formed only recently. This evolution is confirmed by inspection of unpublished *HST* data taken in 2006. Furthermore, the head bubble is dimmer in the 1992 discovery image of Cordes et al. (1993) than it is in Fig. 1 or in the 1995 image shown by Chatterjee & Cordes (2002).

For the middle and bottom bubbles, the predicted expansion rates are slower, $\sim 0.02 \text{ yr}^{-1}$. This is difficult to detect from the ground. It may be detectable over the 12 years spanned by the *HST* images, but given the low signal-to-noise ratio, this will require detailed modelling, which we have not attempted.

The lower proper motions for the middle and bottom bubbles also imply predicted limb surface brightnesses about 3 times fainter than for the head bubble. This is roughly consistent with the observed ratio of 4 (Table 1).

4. RAMIFICATIONS

We found that we could roughly reproduce the Guitar Nebula assuming the jet-like back flow from the pulsar bow shock becomes unstable and dissipates rapidly, causing expanding bubbles. If this were to happen generally, one might expect other sources with jets or bow shocks to show Guitar-like bubbles, yet none appear to be known. For jet sources, this may not be surprising: many jets are denser than the medium they move through, and hence more stable, and disruptions that do occur may be difficult to distinguish from, e.g., changes in jet orientation.

For other bow shocks, the absence of bubbles may partly be a selection effect: most have much larger stand-off radii than the Guitar, and hence any bubbles would be at correspondingly larger distances, where they might be missed, especially as they would be fainter than the bow shock (or even invisible if the expansion velocity became too low or if radiative effects became important; both perhaps relevant especially for stellar wind bow shocks). The one possible exception is PSR B0740–28, which has a $H\alpha$ bow shock with a relatively small stand-off radius of $\theta_0 = 1.0''$ as well as “shoulders” further behind (Jones et al. 2002). If related to an instability, one infers $15 \lesssim \lambda/\theta_0 \lesssim 60$, of the same order as we see for the Guitar. It would be interesting to obtain deeper images further behind the bow shock.

In some pulsar bow shocks, the shocked pulsar wind is ob-

served directly, by its synchrotron emission (for an overview, Kargaltsev & Pavlov 2008). For many, including the Guitar (Hui & Becker 2007b), emission is seen only close to the pulsar, likely at the pulsar wind termination shock. Some, however, have much longer tails. The longest belongs to the “Mouse,” associated with PSR J1747–2958. This nebula, with $\theta_0 \approx 0''.75$, shows a bulbous structure ~ 1.5 behind the pulsar (the Mouse’s body), but also a smooth, straight tail of $12'$, without a clear end (Gaensler et al. 2004). Scaling with the stand-off distances, one might identify the Mouse’s body with the equivalent of the Guitar’s head bubble. The long tail has a size equivalent to the bottom bubble, but, apart from changes in polarisation, shows little structure (Yusef-Zadeh & Bally 1987). This would seem inconsistent with any bubbles being formed, and thus is puzzling in the context of our model.

For two other pulsar bow shocks with long tails, the observations match expectations better. For PSR J1509–5850, with $\theta_0 \approx 0''.5$, the X-ray tail extends for $\gtrsim 5.6$ and shows clear structure, with a change in brightness at 1.3 , a kink at $3'$, and a bright radio spot coincident with its end point (Hui & Becker 2007a; Kargaltsev et al. 2008). Comparing with the large bubbles in the Guitar, the typical length scale of ~ 1.5 for the knots and kinks is about a factor 3 larger, roughly consistent with the ratio of the stand-off distances. For PSR B1929+10, with $\theta_0 \approx 2''.3$, the tail extends up to $10'$ and again shows substantial structure, with brightenings at $\sim 2'$ and $\sim 5'$, the latter coincident with a radio feature (Becker et al. 2006; Misanovic et al. 2007). Again scaling with the stand-off radii, the $5'$ feature could be similar to the head bubble in the Guitar.

Overall, we conclude that our model of instabilities in a bow shock back flow roughly reproduces observations of the

Guitar Nebula, without the need to appeal to variations in the density of the ambient medium, nor to energy sources beyond what is expected to be carried by the back flow. It also seems consistent with what is seen in other pulsar bow shocks. The model could be tested further both with observations and simulations. Observationally, one test would be to measure the expansion velocities in the Guitar bubbles, either by determining proper motions, or by spectroscopy (from the broad component of the $H\alpha$ profile, as done for non-radiative shocks in supernova remnants; Raymond 1991). Given the observed $H\alpha$ surface brightness, this would allow one to estimate the ambient density, which should be similar to that at the location of the bow shock in our model, but substantially lower if the bubbles reflect density variations (Cordes et al. 1993; Chatterjee & Cordes 2004).

Simulations of bow shocks that extend to larger scales might show whether instabilities in fact lead to bubbles or rather to more continuous structure, or whether perhaps the process is sufficiently stochastic that both can occur (possibly leading to a shape like the Guitar’s neck). If bubbles form, the simulations might also shed light on details of the morphology, such as the closed appearance at the back of the head and bottom bubbles.

We thank Maxim Lyutikov, Ruben Krasnapolsky, and Chris Matzner for insight in bow shock and jet instabilities, and the referee for constructive criticism. This research started during a visit to the IAS, which is thanked for hospitality. It made use of ADS and SIMBAD, and draws upon NOAO archival data from the Champlane survey.

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